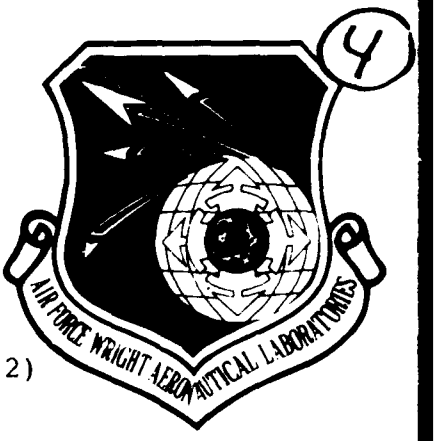

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CORRELATION OF PORTABLE WEAR METAL ANALYZER (PWMA-2) AND BAIRD A/E35U-3 SPECTROMETER OIL ANALYSIS DATA

Robert L. Wright

Lubrication Branch
Fuels and Lubrication Division

November 1988

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AERO PROPULSION AND POWER LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
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Tables for correlation of the Perkin-Elmer portable wear metal analyzer, version two (PWMA-2) readings (in ppm) with the Baird A/E35U-3 atomic emission spectrometer readings (also in ppm) were prepared by curve fitting of data from aircraft, bearing test rig, and organometallic-Silicon oil samples analyzed on both instruments. Each of the nine wear metal elements (Fe, Ag, Al, Cr, Cu, Mg, Ni, Si, Ti) was separately fitted to linear, logarithmic, power law, and low order polynomial curves. Power law curve fits were best for almost all the elements, especially in the important low concentration range (0-5 ppm), where Air Force jet turbine engines typically operate. The power law curve was applied to all elements to construct the correlation tables with a general uncertainty in table values equal to about 0.5 to 1 ppm or 10%, whichever is greater. The coefficients of determination for the power law curve fits ranged from 0.935 for Al to 0.993 for Fe. The fit for Si was very poor for any type of curve (best coefficient of determination = 0.564 for power curve fit) and therefore Si was not included in the tables because the confidence level for its values is very low. trace metals.

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Chromium Copper Magnesium Nickel Silicon (1) Aluminum

PREFACE

This technical report was prepared by the Lubrication Branch, Fuels and Lubrication Division, Aero Propulsion and Power Laboratory, Air Force Wright Aeronautical Laboratories (AFWAL), Air Force Systems Command (AFSC), Wright-Patterson Air Force Base, Ohio. The work herein was accomplished under Project 3048, Task 304806, Work Unit 30480626, "Turbine Engine Lubricant Research," during the period of October 1988 to November 1988 with Mr Robert L. Wright as Project Engineer.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

SECTION I

INTRODUCTION

It was requested by the Air Force Oil Analysis Program Office that correlation of readings generated by the portable wear metal analyzer, version two (PWMA-2) oil analysis spectrometer, manufactured by Perkin-Elmer (P-E) Corporation with readings generated by the Air Force's home-base oil analysis spectrometer, the A/E35U-3, manufactured by Baird Atomic Corporation be attempted. The two instruments are both very accurate and repeatable, and are capable of detecting trends in engine wear metal concentrations, consistent with their own results. Due to the difference in the basic technologies of the two instruments (PWMA-2 is based on graphite furnace atomic absorption technology and A/E35U-3 is based on rotrode atomic emission technology) and to the fact they are calibrated with different type oil standards, the instruments generate different absolute values when analyzing the same sample. However, if both instruments are accurate and repeatable, it is theoretically possible to correlate their data.

A field test and evaluation of the capabilities of the PWMA-2 was conducted in Aug-Oct 88 at three U. S. Air Force bases. Oil samples from jet turbine engine aircraft (F-4, F-15, F-16, T-37, T-38, and others) and an Alcor Corporation bearing test rig, as well as specially prepared organometallic oil samples were used as the data base. In conjunction with this test and evaluation of the PWMA-2, the Baird A/E35U-3

spectrometer was also employed to analyze a great number of these same samples. Data generated are used here to establish correlation algorithms and tables of equivalent values for the two instruments. It is realized the manner in which the instruments detect wear metal element concentrations is a function of the each instrument's unique capabilities and the physical properties of each element. Therefore, it is reasonable to assume the correlation is different for each element. The approach taken was to correlate the elements separately, instead of attempting to construct a generic correlation algorithm that was independent of element. Fitting of data from oil samples analyzed on both instruments to linear, logarithmic, power law, and low order polynomial curves was attempted. It was seen early in the data correlation analyses, that the only types of curves giving reasonable fits to the data for each element were linear and power law curves, and these will be the only ones referred to in the remainder of this report.

SECTION II

RESULTS OF SAMPLE DATA TREATMENT

Wherever possible, aircraft oil sample data were used in the curve fitting analyses. There were about 440 turbine engine aircraft samples mutually analyzed by both PWMA-2 and A/E35U-3. Most of these analyses yielded data in very low (0-2 ppm) concentrations for all elements. A few analyses yielded concentrations in the 3-5 ppm range, and rarely, for some elements, yielded concentrations above 5 ppm. The methodology used to establish data points from the aircraft oil sample analyses for correlation of each element was to take a specific concentration as read by the A/E35U-3 and compute the trimmed mean of all PWMA-2 readings for the same samples. For example, there were 96 sample cases where the A/E35U-3 read 1 ppm for Fe. The trimmed mean for PWMA-2 readings for these same 96 sample cases was 0.36 ± 0.15 ppm. This methodology was used because the A/E35U-3 is the established spectrometer and because its results are reported in integer values of ppm, while the PWMA-2 results are reported to 0.1 ppm. So this established one data point for Fe, with A/E35U-3 = 1 ppm and PWMA-2 = 0.36 ppm. All other aircraft oil sample data points were established in the same manner. There were 380 cases for Fe where the A/E35U-3 read greater than 0 ppm. For Ag there were no cases of either spectrometer reading greater than 0. For Al there were 2 cases where A/E35U-3 read greater than 0. For Cr there were 43 cases where A/E35U-3 read greater than 0. For Cu there were 133 cases where A/E35U-3 read greater than 0. For Mg there were 25 cases

where A/E35U-3 read greater than 0. For Ni there were 230 cases where A/E35U-3 read greater than 0. For Si there were 154 cases where A/E35U-3 read greater than 0. For Ti there were 262 cases where A/E35U-3 read greater than 0. If it was noticed that PWMA-2 read greater than 0 when A/E35U-3 read 0 for any element in more than a few cases, a trimmed mean was established for the PWMA-2 values of these samples and entered as the PWMA-2 value in the correlation table for A/E35U-3 value equal to 0.

Four bearing test rig oil samples supplied by Alcor Corp. were used in the correlation analyses of Fe and Si, since there was significant concentration (> 1 ppm) of only these two elements in the samples. The methodology used to establish Fe and Si data points from these samples was straightforward. The trimmed means for each sample on each instrument were used to establish four data points for Fe and Si correlations. About 40 analyses of each sample were done on PWMA-2 and 20 analyses of each sample on A/E35U-3.

Six organometallic compounds in oil samples were prepared by the Joint Oil Analysis Program, Technical Service Center (JOAP/TSC). These samples contained significant concentrations of each element in each sample. Six data points for each element were established just as in the case for the Alcor bearing rig samples. Approximately 40 analyses of each sample were accomplished on PWMA-2 and 20 analyses of each sample on A/E35U-3.

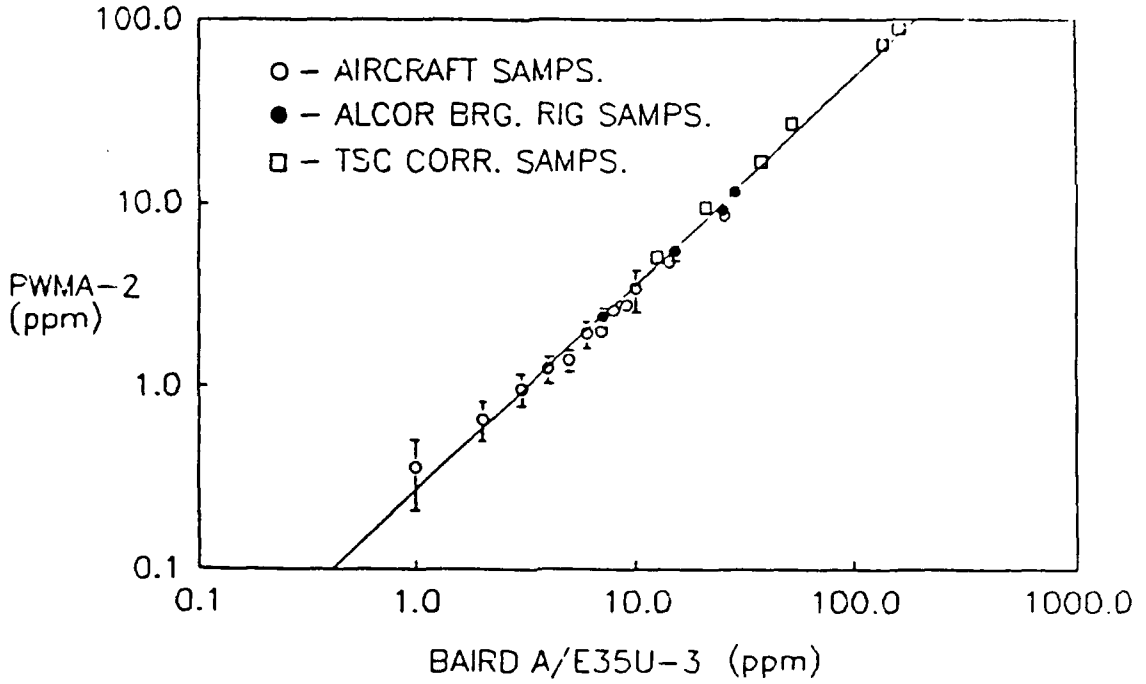
Finally, five organometallic compounds in oil samples were prepared by P-E Corp. These samples were made up as standards

with which to calibrate the PWMA-2 and contained 10, 30, 50, 75, and 100% of the dynamic low-range concentration detection limit for each element. In addition three organometallic samples were prepared by P-E for calibration of Fe and Cu in 50, 75, and 100% of the dynamic high-range concentration detection limit. In low-range analysis, the PWMA-2 detects Ag and Cr up to 10 ppm, Al and Mg up to 15 ppm, Cu, Ni, and Ti up to 20 ppm, and Fe up to 30 ppm. In high-range analysis, PWMA-2 detects Cu up to 40 ppm and Fe up to 80 ppm. These are the nominal 100% dynamic range concentration detection limits for PWMA-2, with the actual detection limits being about 120% of the nominal detection limits. These P-E standard samples were used to establish data points for all elements except Fe, Si, and Ti. Fe and Si were considered to have enough aircraft and JOAP/TSC sample data points to not need the additional P-E standard sample data points. Data was not available for Ti in A/E35U-3 analyses of the P-E standard samples. Methodology for establishing data points from these samples was to assign the PWMA-2 value as the nominal dynamic range concentration of each element in each sample and take the trimmed mean of all the A/E35U-3 analyses for each element in each sample as the A/E35U-3 value. This gave five data points for all elements except Cu which was given eight data points. The reasons the nominal concentrations were assigned as the PWMA-2 values were that these are the samples that PWMA-2 is calibrated with and the overall means of all PWMA-2 analyses of these standard samples utilized as verification "burns" were extremely close to the nominal dynamic

range concentrations. Approximately 10 analyses of each sample were carried out with A/E35U-3.

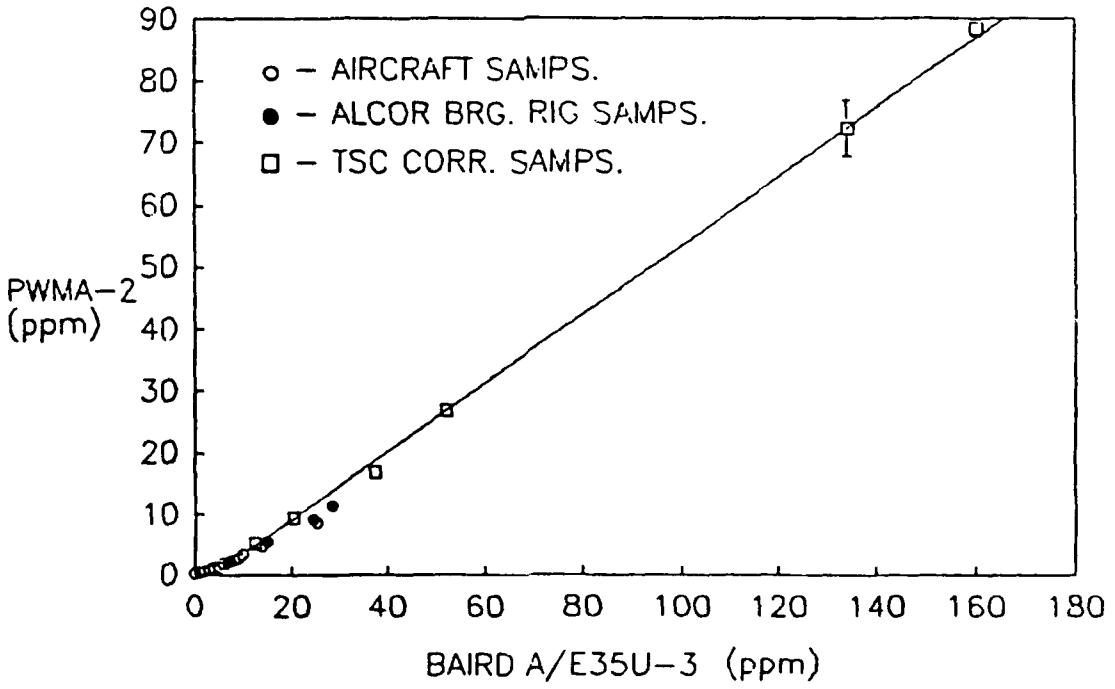
Once all data points for all nine elements were established, curve fitting of the data points was attempted. Since the A/E35U-3 is the established spectrometer, it's data point values were assigned as the independent or "x" variable. The PWMA-2 values were assigned as the dependent or "y" variable. Both linear and power law curve fitting techniques gave good correlation for most of the elements, with power law correlation being slightly better in most cases. Curve fits were accomplished by using method of least squares calculator programs. The linear equation is of the form $y = bx + a$. This can be represented graphically by plotting y versus x on linear graph paper with b equal to the slope of the best fit straight line and a equal to the y axis intercept. The power law equation is of the form $y = ax^b$. Graphic representation is accomplished by plotting y versus x on log-log graph paper with the exponent, b, equal to slope of the best fit straight line and a equal to the inverse logarithm of the y intercept. Plots of the data points and their best linear and power curve fits are shown in Figures 1-9. Also shown on these plots are the best linear and power curve equations along with the coefficient of determination for each equation. The coefficient of determination is an excellent measure of the goodness of fit for a particular curve. It is the proportionate reduction of total variation associated with the use of the independent variable (ref 1) and is equal to the square of the correlation

POWER CURVE EQ: PWMA−2 = 0.269 $(AE)^{1.126}$, COEFF. OF DETERM. = 0.993



a) Logarithmic plot

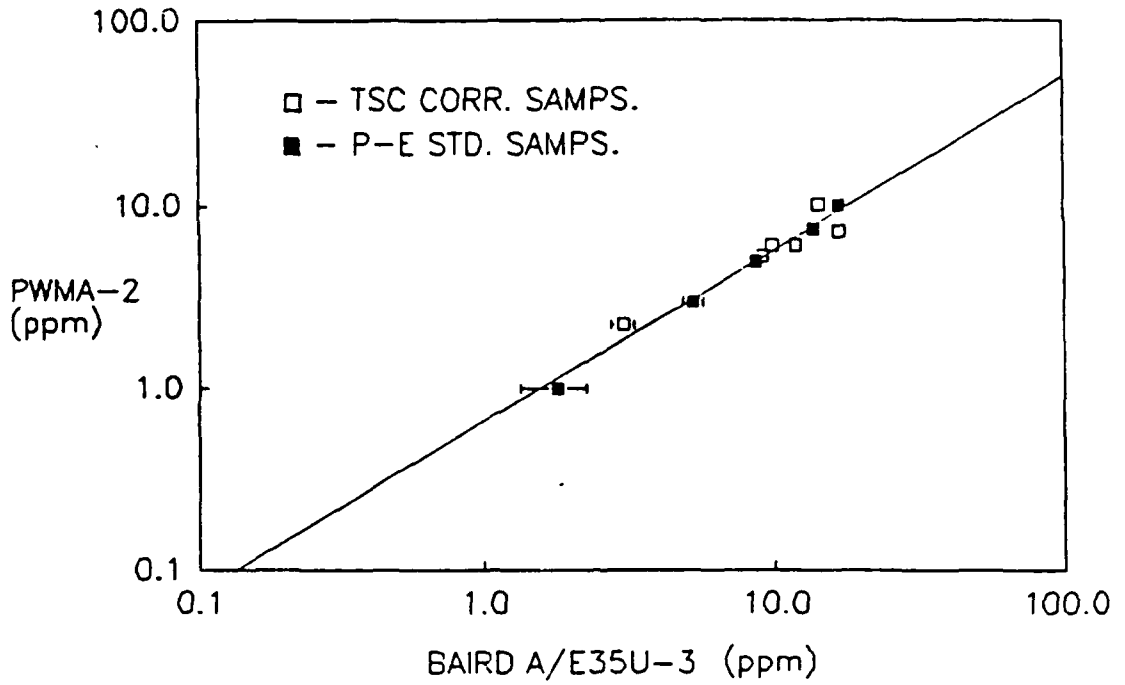
LINEAR EQ: PWMA−2 = 0.554 AE − 1.99, COEFF. OF DETERM. = 0.996



b) Linear plot

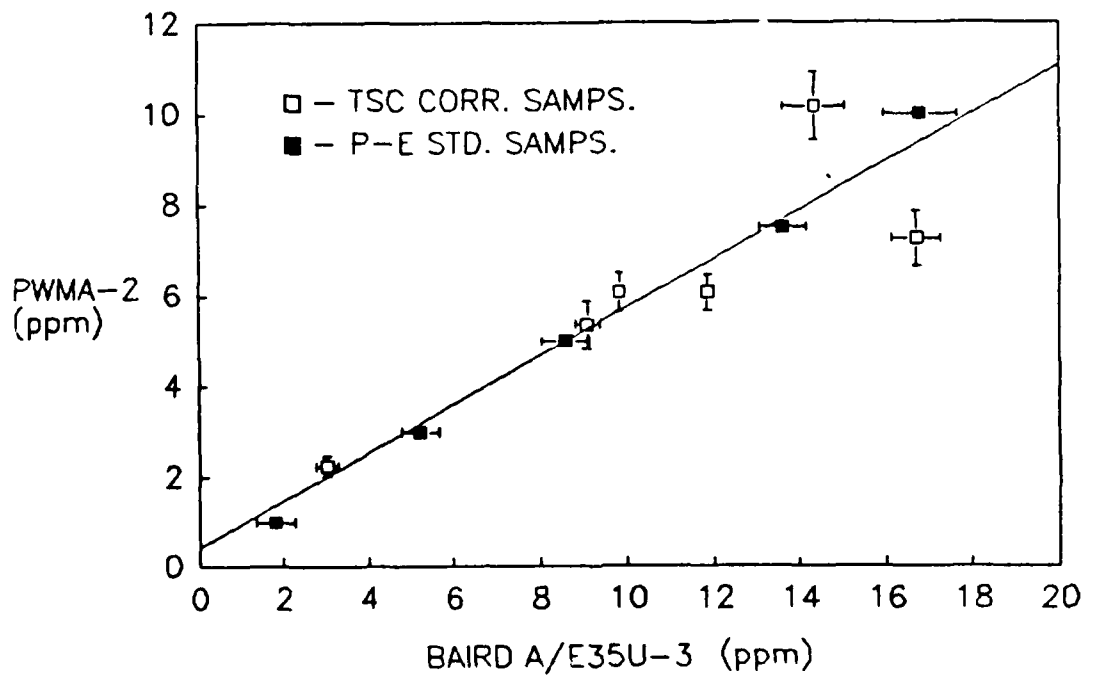
Figure 1. Logarithmic and linear plots of PWMA-2 vs. A/E35U-3 data for Fe

POWER CURVE EQ: PWMA-2 = 0.66 $(AE)^{0.94}$, COEFF. OF DETERM. = 0.960



a) Logarithmic plot

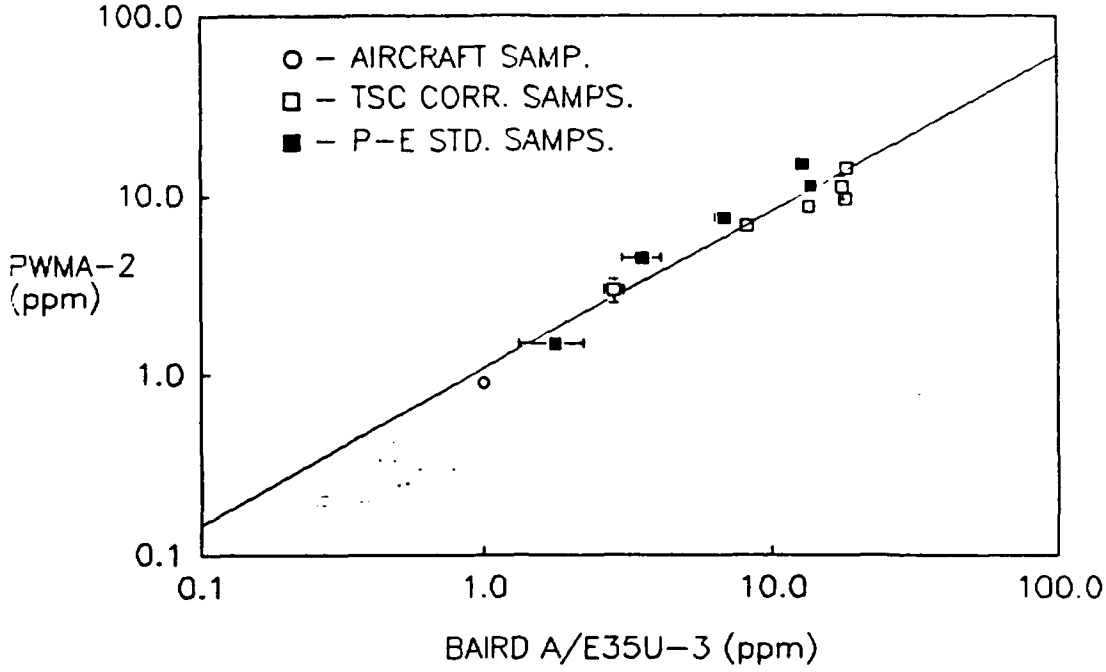
LINEAR EQ: PWMA-2 = 0.53 AE + 0.42, COEFF. OF DETERM. = 0.940



b) Linear plot

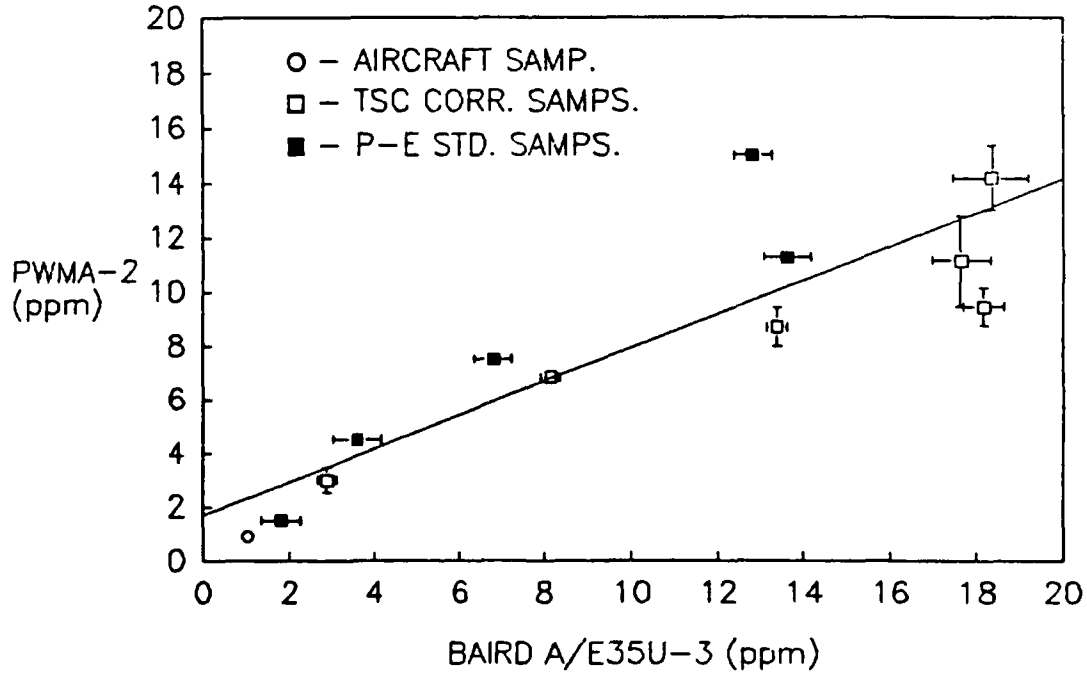
Figure 2. Logarithmic and linear plots of PWMA-2 vs. A/E35U-3 data for Ag

POWER CURVE EQ: PWMA-2 = 1.09 $(AE)^{0.874}$, COEFF. OF DETERM. = 0.935



a) Logarithmic plot

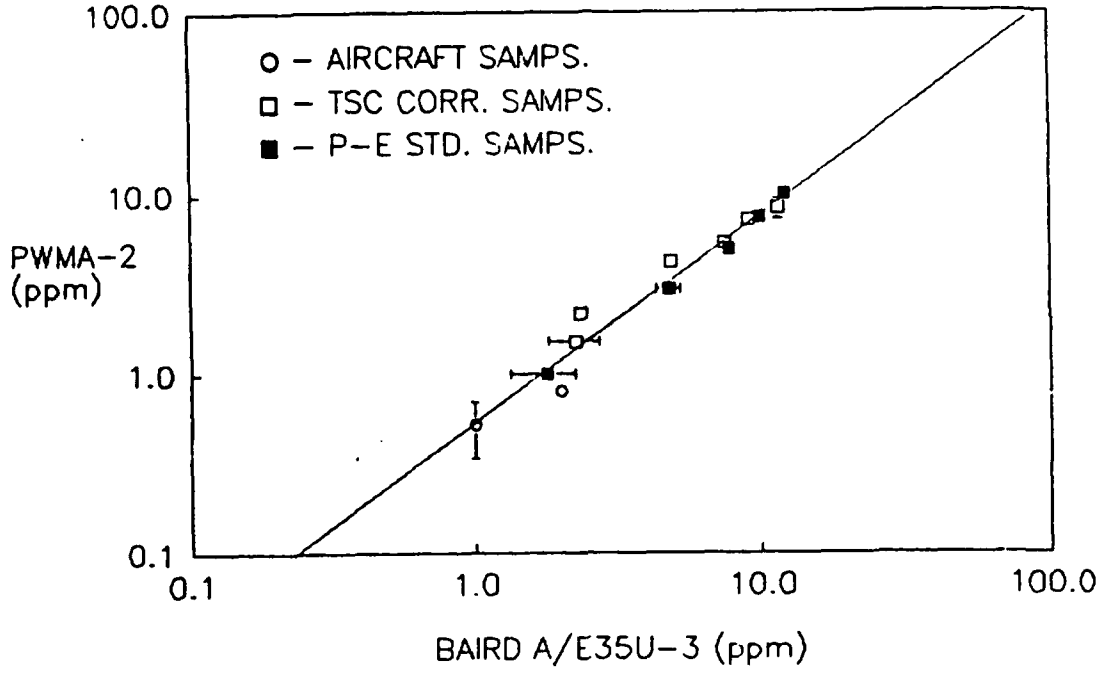
LINEAR EQ: PWMA-2 = 0.624 AE + 1.68, COEFF. OF DETERM. = 0.774



b) Linear plot

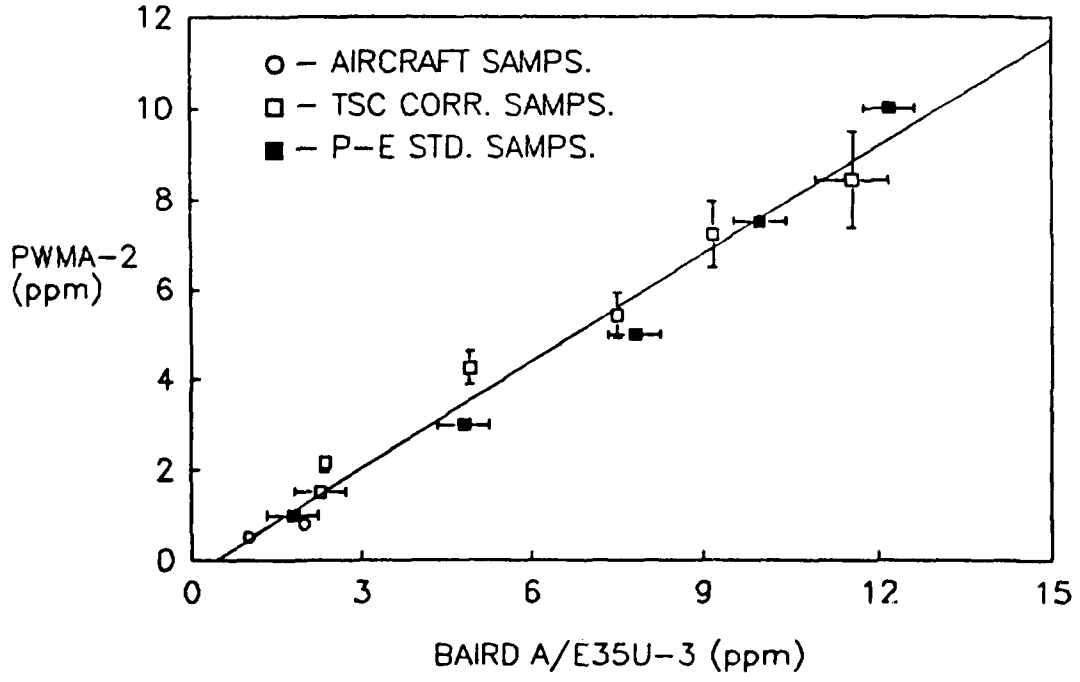
Figure 3. Logarithmic and linear plots of PWMA-2 vs. A/E35U-3 data for Al

POWER CURVE EQ: PWMA−2 = 0.535 $(AE)^{1.156}$, COEFF. OF DETERM. = 0.963



a) Logarithmic plot

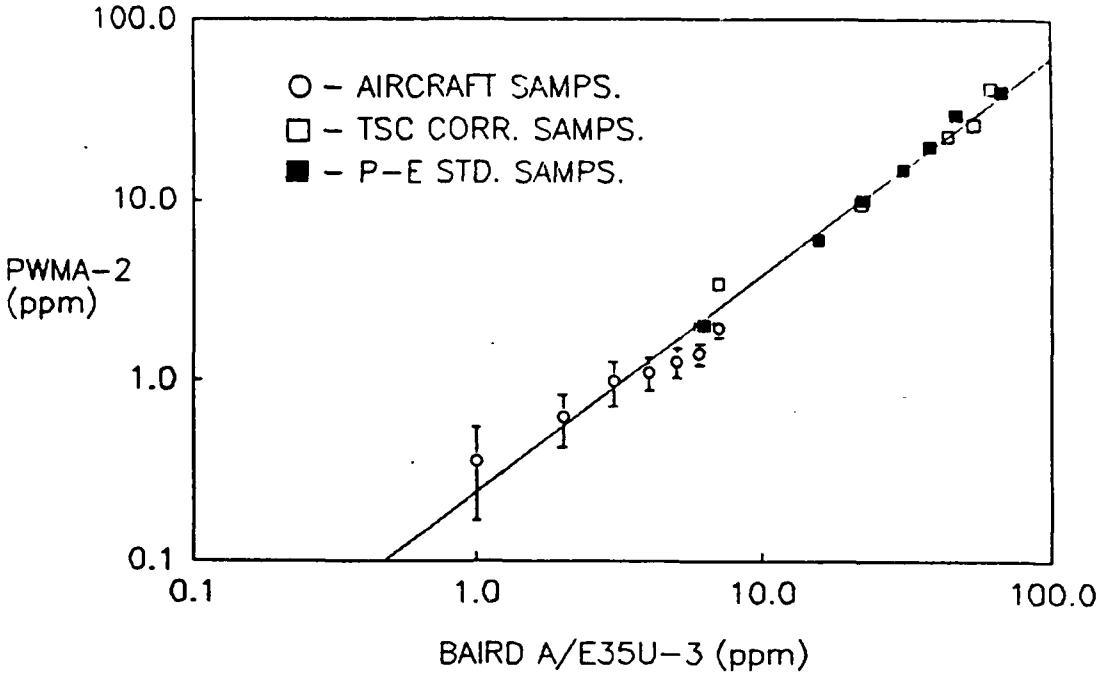
LINEAR EQ: PWMA−2 = 0.79 AE − 0.335, COEFF. OF DETERM. = 0.977



b) Linear plot

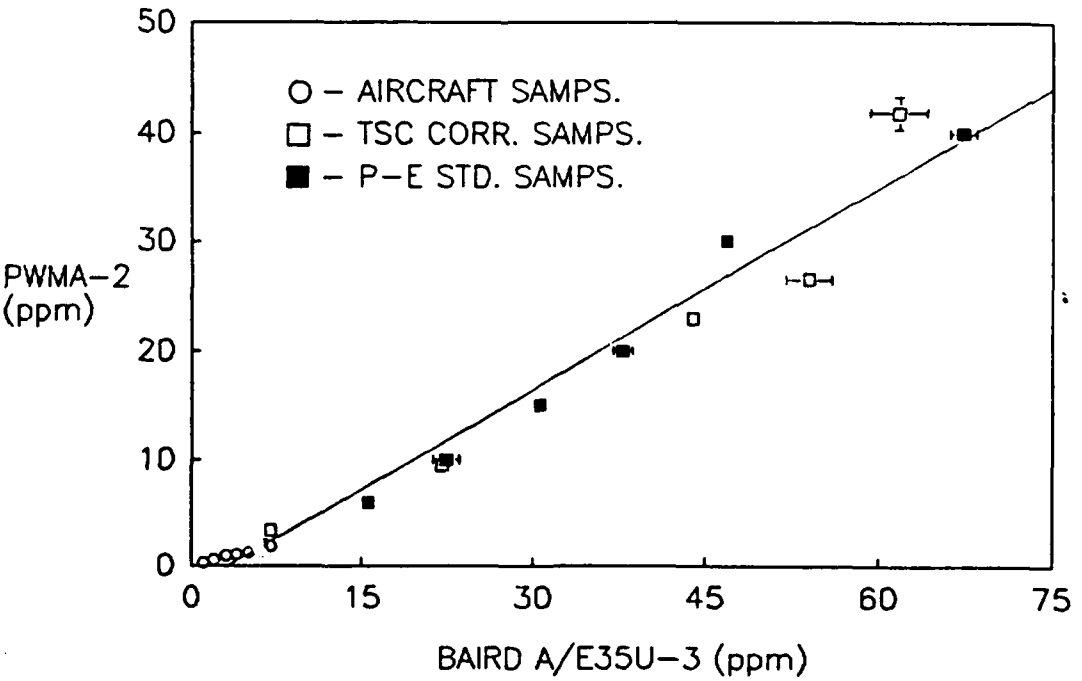
Figure 4. Logarithmic and linear plots of PWMA-2 vs. A/E35U-3 for Cr

POWER CURVE EQ: PWMA−2 = 0.244 $(AE)^{1.20}$, COEFF. OF DETERM. = 0.983



a) Logarithmic plot

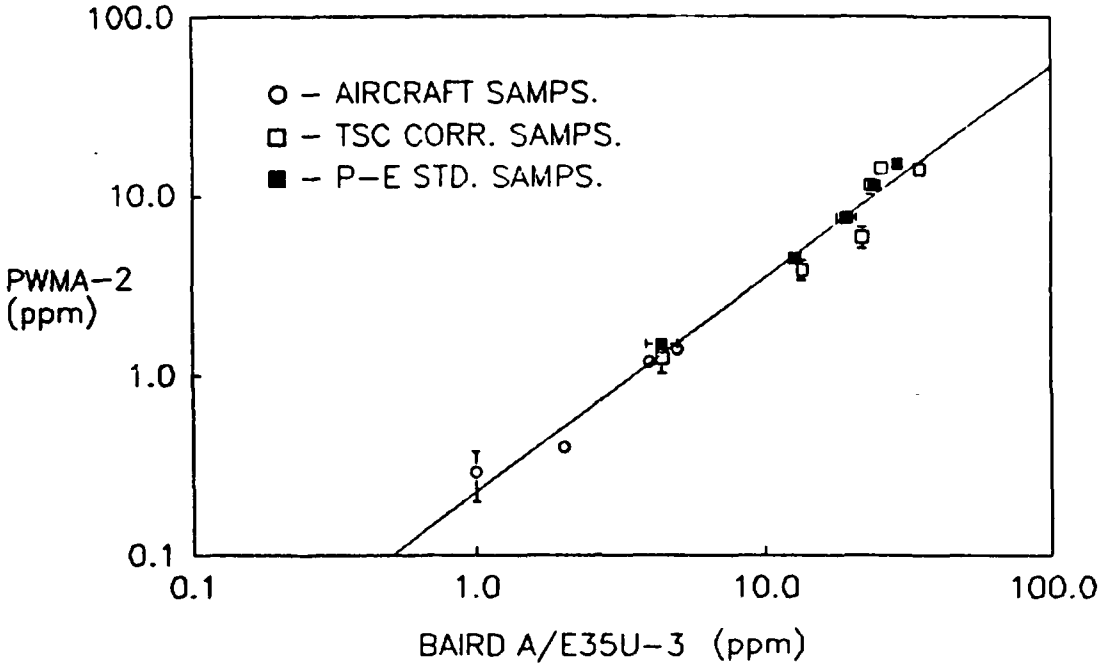
LINEAR EQ: PWMA−2 = 0.616 AE − 2.00, COEFF. OF DETERM. = 0.973



b) Linear plot

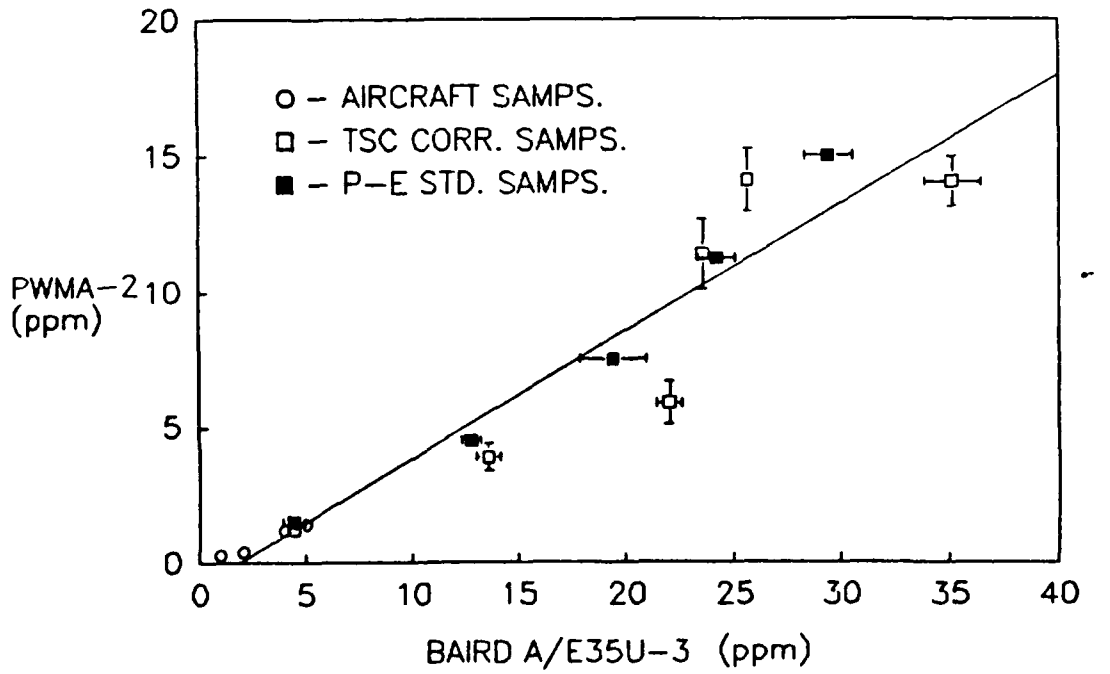
Figure 5. Logarithmic and linear plots of PWMA-2 vs. A/E35U-3 data for Cu

POWER CURVE EQ: PWMA−2 = 0.226 $(AE)^{1.186}$, COEFF. OF DETERM. = 0.977



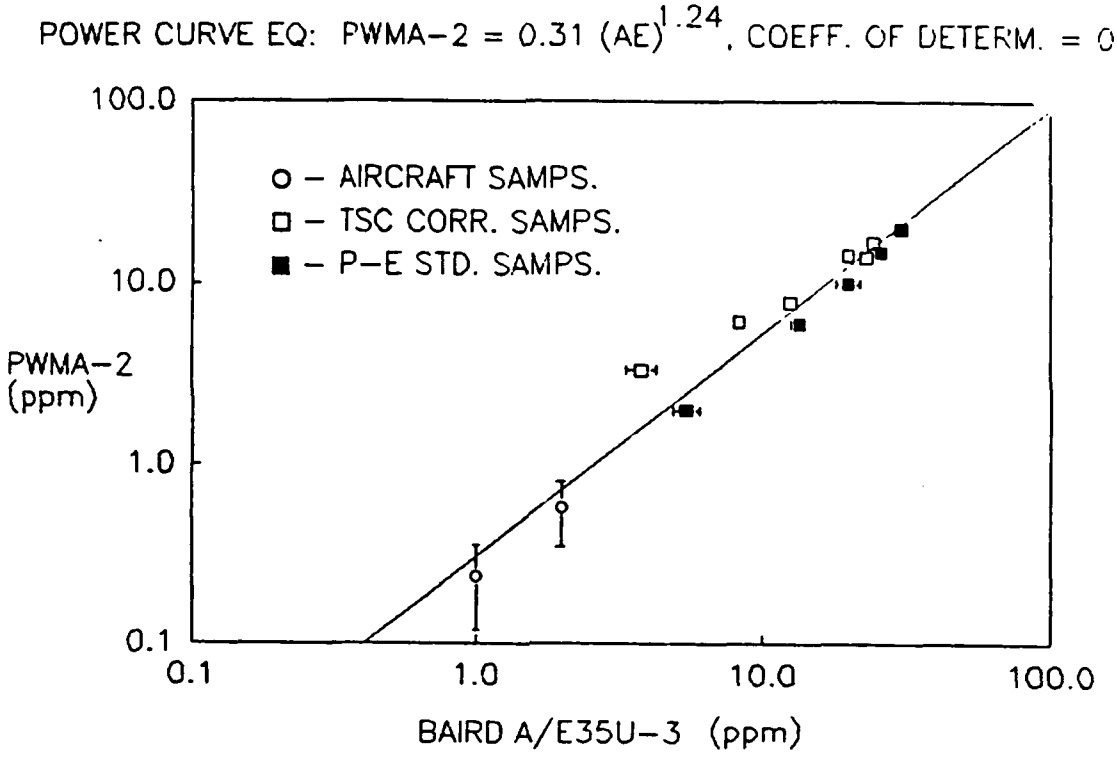
a) Logarithmic plot

LINEAR EQ: PWMA−2 = 0.47 AE − 0.875, COEFF. OF DETERM. = 0.919

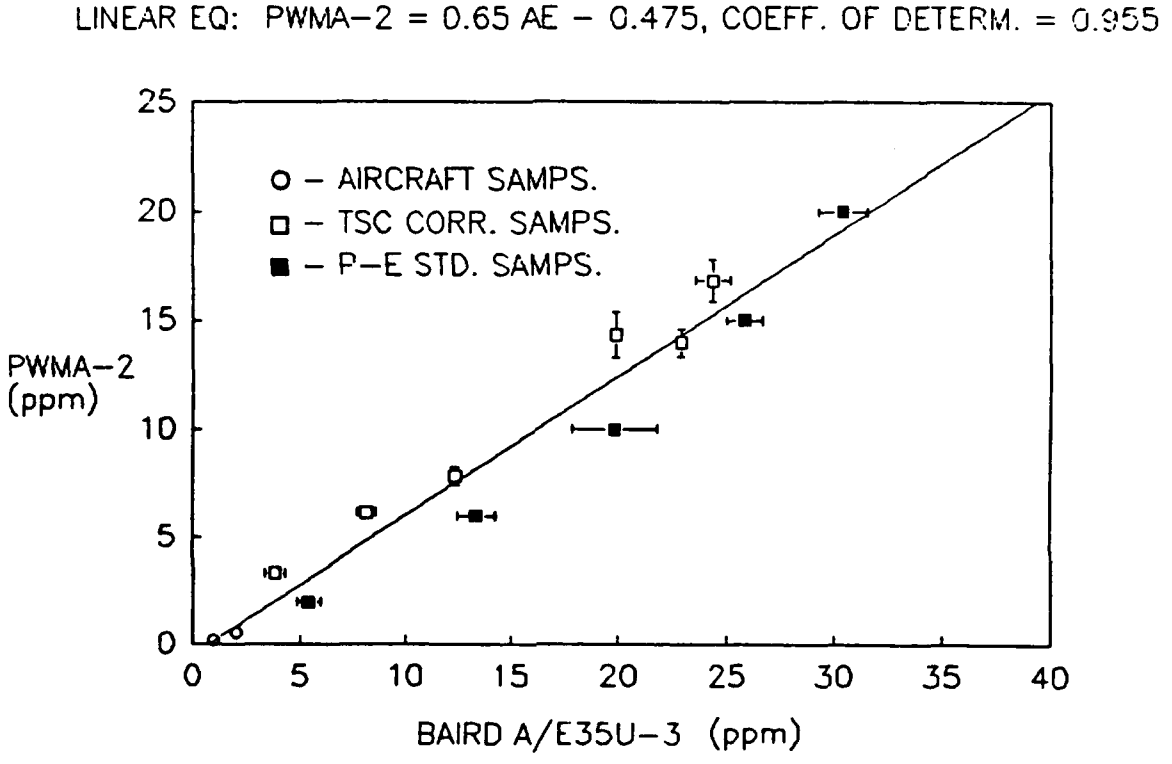


b) Linear plot

Figure 6. Logarithmic and linear plots of PWMA-2 vs. A/E35U-3 data for Mg

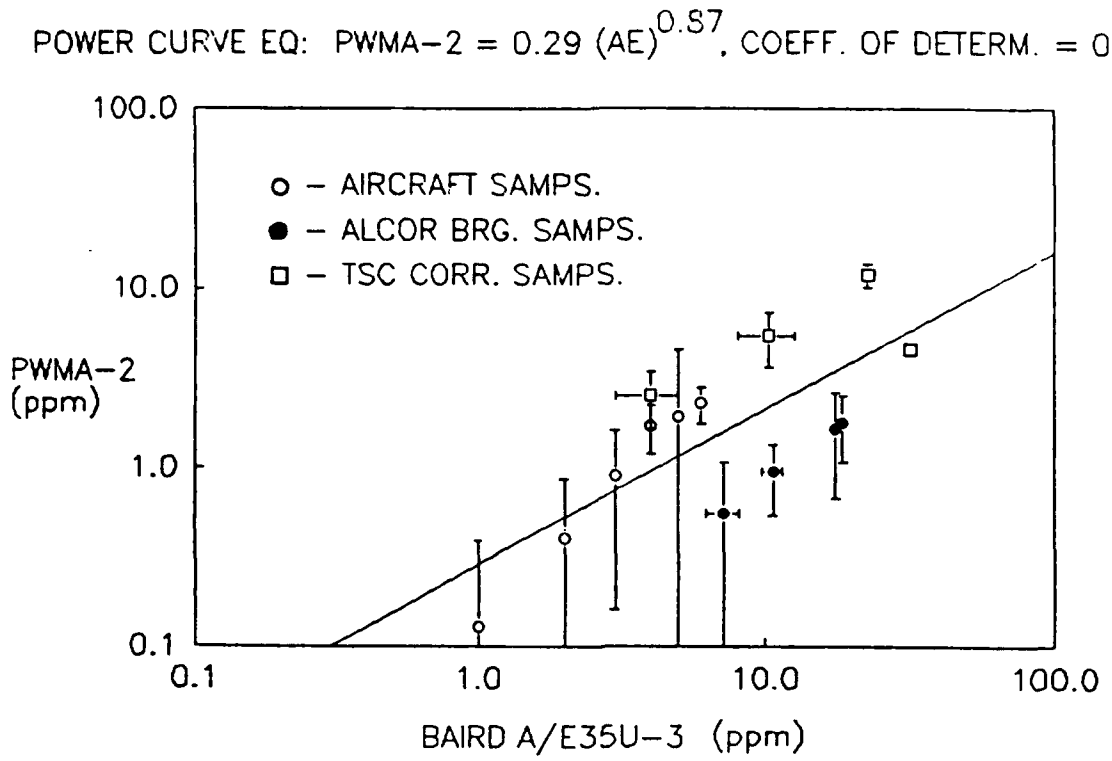


a) Logarithmic plot

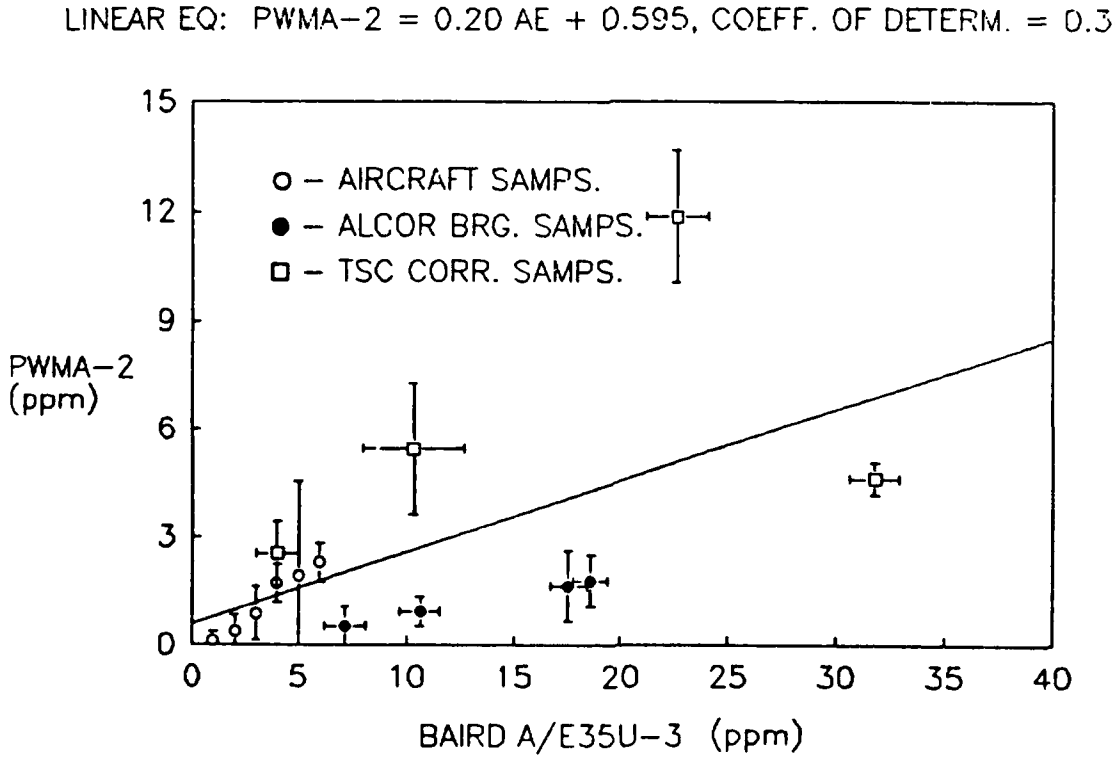


b) Linear plot

Figure 7. Logarithmic and linear plots of PWMA-2 vs. A/E35U-3 data for Ni

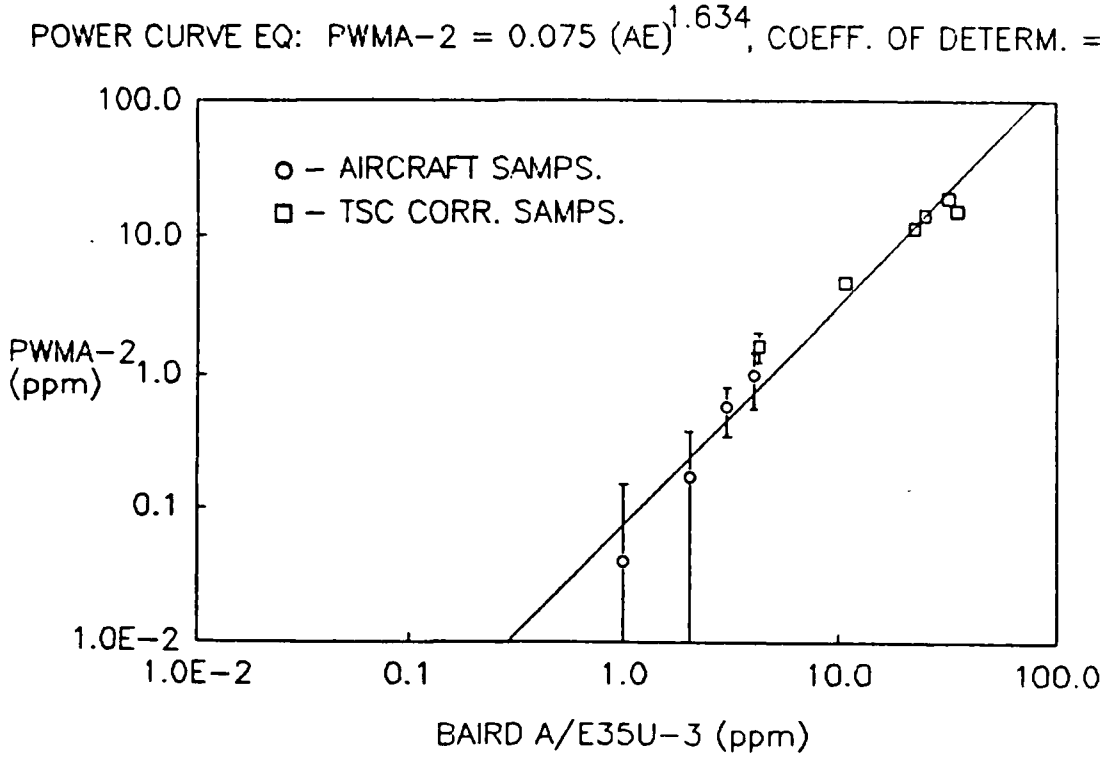


a) Logarithmic plot

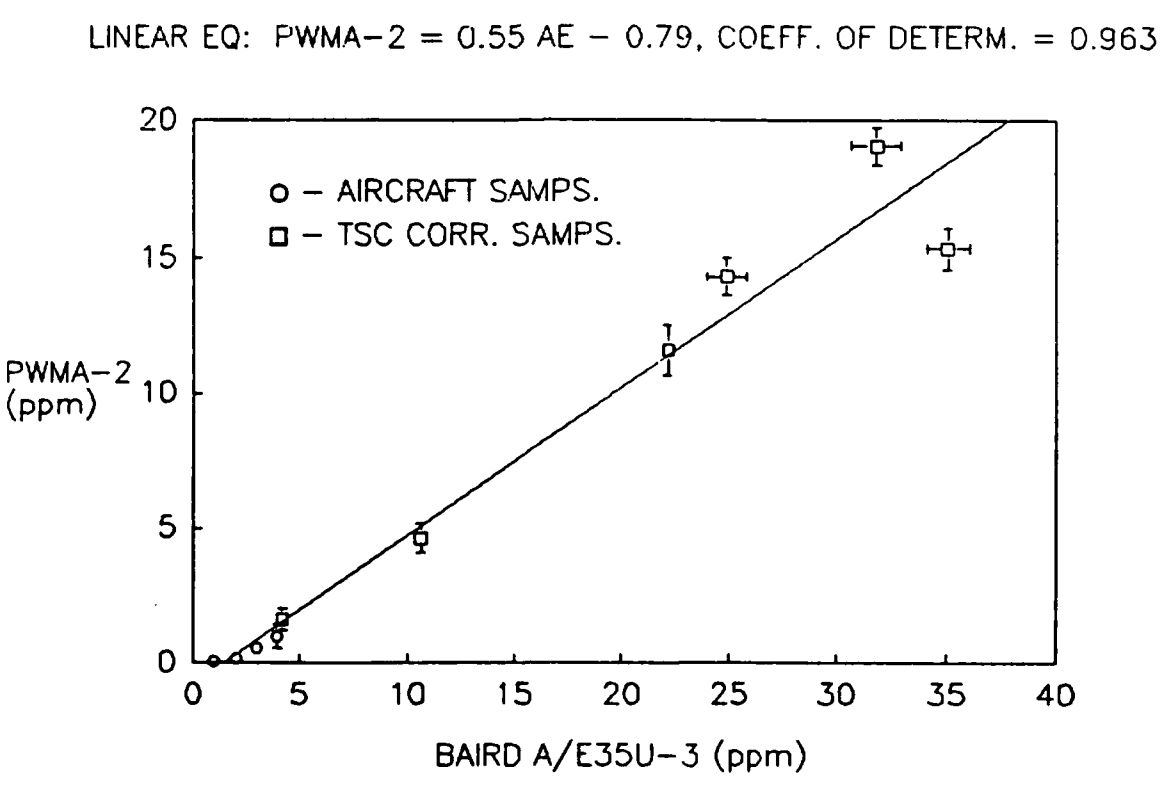


b) Linear plot

Figure 8. Logarithmic and linear plots of PWMA-2 vs. A/E35U-3 data for Si



a) Logarithmic plot



b) Linear plot

Figure 9. Logarithmic and linear plots of PWMA-2 vs. A/E35U-3 data for Ti

coefficient. A coefficient of determination of 1 means a perfect fit. The coefficient of determination gives a more reasonable idea of the goodness of fit than does the more often used correlation coefficient. For example, a correlation coefficient of 0.95 may not indicate a truly superior data fit, while a coefficient of determination of 0.95 indicates a truly good fit equal to a correlation coefficient of 0.975.

Table 1 shows the total number of sample analyses considered for each element in this correlation study as well as a compilation of the coefficients of determination for the best fit linear and power curve equations for each element.

TABLE 1. GOODNESS OF FIT FOR PWMA-2 vs. BAIRD A/E35U-3 CORRELATION

	TOTAL SAMPS ANALYZED		COEFFICIENT OF DETERMINATION	
ELEMENT	PWMA-2	A/E35U-3	LINEAR FIT	POWER CURVE FIT
Fe	750	590	0.996	0.993
Ag	240	125	0.940	0.960
Al	240	125	0.774	0.935
Cr	280	170	0.977	0.963
Cu	330	240	0.973	0.983
Mg	270	150	0.919	0.977
Ni	460	355	0.955	0.955
Si	395	275	0.349	0.564
Ti	500	380	0.963	0.983

SECTION III

DISCUSSION

The goal of this correlation study was to construct tables of values relating PWMA-2 and A/E35U-3 data. A table of equivalent PWMA-2 values given a particular A/E35U-3 value is shown in Table 2. A table of equivalent A/E35U-3 values given a particular PWMA-2 value is shown in Table 3.

Table 2 is constructed from the best fit power curve equations shown in Figures 1-7, and Figure 9. The best fit power curve equations were chosen because they gave the highest coefficients of determination for 6 of the 9 elements as compared to best fit linear equations. One element (Ni) had equal coefficients of determination for both types of curve fits and two elements (Fe and Cr) had slightly higher linear coefficients of determination. Consideration for the type of fit given at low concentration (0-5 ppm) levels was also used in choosing the best type of correlation equation. It can be seen the linear equations have a weakness at low concentrations because of their non-zero intercepts. At A/E35U-3 concentrations of 1 or 2 ppm, the addition of the intercept in the linear equation sometimes gives negative or unrealistic PWMA-2 values. Since Air Force jet turbine engines typically operate in these low concentration ranges for all wear metal elements, it was decided to use the power curve equation for all elements because it does not have an intercept term and gives calculated values very close to the actual data point values at these important low concentration levels.

TABLE 2. PWMA-2 vs. BAIRD A/E35U-3 SPECTROMETER CORRELATION TABLE *

TABLE FOR CONVERSION OF AE-3 READINGS INTO EQUIVALENT PWMA-2 READINGS (ppm)

AE-3 \ PWMA-2	Fe	Ag	Al	Cr	Cu	Mg	Ni	Ti
0	0.2	0	0.3	0.2	0.2	0.1	0.1	0
1	0.4	0.7	1.1	0.5	0.4	0.3	0.3	0.1
2	0.6	1.3	2	1.2	0.6	0.5	0.6	0.2
3	0.9	1.9	2.8	1.9	0.9	0.8	1.2	0.5
4	1.3	2.4	3.6	2.6	1.3	1.2	1.7	0.8
5	1.6	3	4.4	3.4	1.7	1.5	2.2	1
6	2	3.6	5.2	4.2	2	1.9	2.8	1.4
7	2.4	4.1	6	5	2.5	2.3	3.4	1.8
8	2.8	4.7	6.7	5.9	2.9	2.7	4	2.2
9	3.2	5.2	7.4	6.8	3.4	3.1	4.7	2.7
10	3.6	5.7	8.1	7.6	3.8	3.5	5.3	3.2
12	4.4	6.8	9.6	9.4	4.8	4.3	6.7	4.3
14	5.3	7.9	10.9	11.3	5.8	5.2	8.1	5.6
15	5.7	8.4	11.6	12	6.3	5.6	8.8	6.2
16	6.1	8.9	12.3		6.8	6.1	9.5	7
18	7	10	13.6		7.8	7	11	8.4
20	7.8	11	14.9		8.9	7.9	12.6	10
22	8.7	12	16.2		10	8.8	14.2	11.7
24	9.6		17.5		11.1	9.8	15.8	13.5
25	10.1				11.6	10.3	16.6	14.4
27	11				12.7	11.3	18.3	16.4
30	12.4				14.4	12.8	20.8	19.4
32	13.3				15.6	13.8	22.5	21.6
35	14.7				17.4	15.3		
37	15.7				18.6	16.4		
40	17.1				20.4	17.9		
45	19.6				23.5			
50	22				27			
55	25				30			
60	27				33			
65	30				36			
70	32				40			
75	35				43			
80	38				47			
90	43							
100	48							
110	54							
120	59							
130	65							
140	70							
150	76							
160	82							
170	88							
175	91							
180	94							

* uncertainty in table values = 0.5 ppm or 10%, whichever is greater.

TABLE 3. BAIRD A/E35U-3 vs. PWMA-2 SPECTROMETER CORRELATION TABLE *

TABLE FOR CONVERSION OF PWMA-2 READINGS INTO EQUIVALENT AE-3 READINGS (ppm)

PWMA-2 \ AE-3	Fe	Ag	Al	Cr	Cu	Mg	Ni	Ti
0	0	0	0	0	0	0	0	0
0.1	0.4	0.1	0.1	0.4	0.5	0.5	0.4	1.2
0.2	0.8	0.3	0.2	0.6	0.8	0.9	0.7	1.8
0.3	1.1	0.4	0.25	0.9	1.2	1.3	1	2.3
0.4	1.4	0.6	0.3	1.2	1.5	1.6	1.2	2.8
0.5	1.7	0.7	0.4	1.4	1.8	2	1.5	3.2
0.6	2	0.9	0.5	1.7	2.1	2.3	1.7	3.6
0.7	2.3	1.1	0.6	1.9	2.4	2.6	1.9	3.9
0.8	2.6	1.2	0.7	2.1	2.7	2.9	2.2	4.3
0.9	2.9	1.4	0.8	2.4	3	3.2	2.4	4.6
1	3.2	1.5	0.9	2.6	3.2	3.5	2.6	4.9
1.1	3.5	1.7	1	2.8	3.5	3.8	2.8	5.2
1.2	3.8	1.9	1.1	3	3.8	4.1	3	5.5
1.3	4	2	1.2	3.2	4	4.4	3.2	5.7
1.4	4.3	2.2	1.3	3.4	4.3	4.7	3.4	6
1.5	4.6	2.4	1.4	3.7	4.5	4.9	3.6	6.3
1.6	4.9	2.6	1.6	3.9	4.8	5.2	3.8	6.5
1.7	5.1	2.7	1.7	4.1	5	5.5	4	6.8
1.8	5.4	2.9	1.8	4.3	5.3	5.8	4.2	7
1.9	5.7	3.1	1.9	4.5	5.5	6	4.3	7.2
2	5.9	3.2	2	4.7	5.8	6.3	4.5	7.5
2.1	6.2	3.4	2.1	4.9	6	6.5	4.7	7.7
2.2	6.5	3.6	2.2	5.1	6.3	6.8	4.9	7.9
2.3	6.7	3.8	2.4	5.3	6.5	7.1	5.1	8.1
2.4	7	3.9	2.5	5.5	6.7	7.3	5.2	8.3
2.5	7.2	4.1	2.6	5.7	7	7.6	5.4	8.6
2.6	7.5	4.3	2.7	5.9	7.2	7.8	5.6	8.8
2.7	7.7	4.5	2.8	6.1	7.4	8.1	5.8	9
2.8	8	4.6	3	6.3	7.6	8.3	5.9	9.2
2.9	8.3	4.8	3.1	6.5	7.9	8.6	6.1	9.4
3	8.5	5	3.2	6.7	8.1	8.8	6.3	9.6
3.2	9	5.3	3.4	7	8.6	9.3	6.6	10
3.4	9.5	5.7	3.7	7.4	9	9.8	6.9	10.3
3.6	10	6.1	3.9	7.8	9.4	10.3	7.3	10.7
3.8	10.5	6.4	4.2	8.2	9.9	10.8	7.6	11.1
4	11	6.8	4.4	8.5	10.3	11.3	7.9	11.4
4.2	11.5	7.1	4.7	8.9	10.7	11.8	8.2	11.8
4.4	11.9	7.5	4.9	9.3	11.2	12.2	8.6	12.1
4.6	12.4	7.9	5.2	9.6	11.6	12.7	8.9	12.4
4.8	12.9	8.2	5.5	10	12	13.2	9.2	12.8
5	13.4	8.6	5.7	10.4	12.4	13.6	9.5	13.1

continued

TABLE 3. (continued)

PMMA-2 \ AE-3	Fe	Ag	Al	Cr	Cu	Mg	Ni	Ti
5.2	13.9	9	6	10.7	12.8	14.1	9.8	13.4
5.4	14.3	9.3	6.3	11.1	13.2	14.5	10.1	13.7
5.6	14.8	9.7	6.5	11.4	13.6	15	10.4	14
5.8	15.3	10.1	6.8	11.8	14	15.4	10.7	14.3
6	15.7	10.4	7.1	12.1	14.4	15.9	11	14.6
6.2	16.2	10.8	7.3	12.5	14.8	16.3	11.3	14.9
6.4	16.7	11.2	7.6	12.8	15.2	16.8	11.6	15.2
6.6	17.1	11.6	7.9	13.2	15.6	17.2	11.9	15.5
6.8	17.6	11.9	8.1	13.5	16	17.6	12.2	15.8
7	18	12.3	8.4	13.9	16.4	18.1	12.4	16.1
7.2	18.5	12.7	8.7	14.2	16.8	18.5	12.7	16.3
7.4	19	13.1	9	14.6	17.2	18.9	13	16.6
7.6	19.4	13.4	9.3	14.9	17.6	19.3	13.3	16.9
7.8	19.9	13.8	9.5	15.2	18	19.8	13.6	17.2
8	20.3	14.2	9.8	15.6	18.4	20.2	13.9	17.4
8.2	20.8	14.6	10.1	15.9	18.7	20.7	14.1	17.7
8.4	21.2	14.9	10.4	16.2	19.1	21.1	14.4	18
8.6	21.7	15.3	10.7	16.6	19.5	21.5	14.7	18.2
8.8	22.1	15.7	10.9	16.9	19.9	21.9	15	18.5
9	22.6	16.1	11.2	17.2	20.3	22.3	15.3	18.7
9.2	23	16.5	11.5	17.6	20.6	22.8	15.5	19
9.4	23.4	16.8	11.8	17.9	21	23.2	15.8	19.2
9.6	23.9	17.2	12.1	18.3	21.4	23.6	16.1	19.5
9.8	24.3	17.6	12.4	18.6	21.7	24	16.3	19.7
10	25	18	12.7	19	22	24.4	16.6	20
10.5	26	19	13	20	23	25	17	20.5
11	27	20	14	20.5	24	26	18	21
11.5	28	21	15	21	25	27	18.5	22
12	29	22	16	22	26	28	19	22.5
13	31		17		28	30	20	23
14	33		19		29	32	22	25
15	35		20		31	34	23	26
16	38		22		33	36	24	27
17	40		23		34	38	25	28
18	42		25		36	40	27	29
19	44				38		28	30
20	46				39		29	31
22	50				43		31	32
24	54				46		34	34
25	56				48			
27	60				51			
30	66				55			

continued

TABLE 3. (continued)

PMMA-2 \ AE-3	Fe	Cu
32	70	58
35	75	63
37	79	66
40	85	70
45	94	78
50	103	
55	113	
60	121	
65	130	
70	139	
75	148	
80	157	
85	166	
90	174	
95	183	

* uncertainty in table values = 1.0 ppm or 10%, whichever is greater.

Table 3 is constructed in similar manner to Table 2, except that equivalent A/E35U-3 values are shown as the dependent variable given a particular PWMA-2 readout. This was accomplished by simply "turning the power curve equations around" and solving for the A/E35U-3 values.

The general uncertainty in the values for Table 2, with the PWMA-2 value as the dependent variable, was calculated using the uncertainty equation of Kline and McClintock (ref 2):

$$w_P = \partial P/\partial AE \times w_{AE}$$

where: w_P = uncertainty in the PWMA-2 value

$\partial P/\partial AE$ = partial derivative of the PWMA-2 equation with respect to the A/E35U-3 value

w_{AE} = uncertainty in the A/E35U-3 value = 1 ppm

The PWMA-2 equation is, of course, the power law expression:

$$P = a(AE)^b$$

The partial derivative of this equation with respect to the A/E35U-3 value is:

$$\partial P/\partial AE = ba(AE)^{b-1}$$

Inserting this expression into the uncertainty equation we find:

$$w_P = ba(AE)^{b-1} \times 1 = ba(AE)^{b-1}$$

It can be seen that the uncertainty in the PWMA-2 value (w_P) will be a function of the AE concentration. However, since the exponent, b, is close to 1 for each element, the functional dependency on AE concentration will not be a strong one and w_P will be approximately equal to a. This works out to be about 0.2 to 1 for most of the elements from 0 to 10 ppm. Above 10 ppm, experience with these two spectrometers indicates an

uncertainty much better than 10% is not to be expected. From this consideration and the above mathematical derivation, it is concluded that a reasonable uncertainty in Table 2 is about 0.5 ppm or 10%, whichever is greater.

For Table 3, with the A/E35U-3 value being the dependent variable, the final uncertainty equation is:

$$w_{AE} = 0.5ba(P)^{b-1}$$

The 0.5 factor comes from the uncertainty in the PWMA-2 value being only about 0.5 ppm as compared to 1 ppm for AE. The exponent, b, remains close to 1 for most elements, but the coefficient a in this equation is approximately equal to the reciprocal of the a value in the analysis with the PWMA-2 value as dependent variable. This increases the magnitude of a to about 1 to 5 for most of the elements in this uncertainty analysis. However, a is multiplied by 0.5, so it is concluded that a reasonable uncertainty for Table 3 is 1 ppm or 10%, whichever is greater.

From Figure 8, it is apparent the curve fit for Si is very poor, even with power law correlation. Since the confidence in Si values calculated between the two instruments would be extremely low, it was decided not to include Si in the correlation tables. There are some theoretically promising "software fixes" for improvement in detection of Si for the PWMA-2. If these "fixes" are successfully made, and a significant amount of field data is accumulated, PWMA-2 to A/E35U-3 correlation for Si should be greatly improved and Si could then be included in the correlation tables.

Although only correlation tables are constructed, if it is desired to have the PWMA-2 generate equivalent A/E35U-3 values, the power law correlation algorithms reported here should be incorported into the PWMA-2 analysis program software to provide equivalent A/E35U-3 values.

SECTION IV

CONCLUSIONS

Power law curve fitting of data from aircraft turbine engine, bearing test rig and organometallic oil samples shows correlation of PWMA-2 with Baird A/E35U-3 spectrometer values is possible. Correlation tables are constructed with the PWMA-2 value as dependent variable and also with the Baird A/E35U-3 as dependent variable to facilitate oil analysis in both deployment and return-to-home-base scenarios. If generation of equivalent A/E35U-3 values is desired when using PWMA-2, the power law correlation algorithms established here should be incorporated into PWMA-2 analysis program software to provide these values.

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2. Kline, S. J. and McClintock, F. A., "Describing Uncertainties in Single-Sample Experiments," Mechanical Eng. 75 (1) 1953.